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Metals reinforced with ceramic fibers or particulates are promising materials for use in new generations of aerospace structures, propulsion devices and energy conversion systems. Furthermore, the controllability of many of these variables opens up the possibility of engineering materials for specific applications, if the effects of alterations in microstructure can be predicted. However, metal-matrix composites often have low ductility and low fracture toughness. An improved understanding of the basic deformation and failure mechanisms is needed to overcome these problems. To this end, research was carried out in three areas: (i) continuum modeling of deformation and fracture in metal-matrix composites, including the interaction between failure mechanisms using phenomenological constitutive relations to characterize each of the main failure modes in metal-matrix composites, reinforcement cracking, interfacial debonding and matrix void nucleation, growth and coalescence; (ii) numerical studies of the propagation of fast cracks along and across interfaces, with a particular focus on understanding crack propagation from a brittle phase into a ductile phase; and (iii) discrete dislocation modeling of matrix plastic deformation in metal-matrix composites with micron size reinforcements.

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1. Summary

Metals reinforced with ceramic fibers or particulates are promising materials for use in new generations of aerospace structures, propulsion devices and energy conversion systems. These materials have high stiffness, strength, and creep resistance, and can be processed using conventional metal-forming techniques. Furthermore, the controllability of many of these variables opens up the possibility of engineering materials for specific applications, if the effects of alterations in microstructure can be predicted. Unfortunately, metal-matrix composites often tend to have low ductility and low fracture toughness. An improved understanding of the basic deformation and failure mechanisms is needed to overcome these problems. The deformation resistance and failure behavior of metal-matrix composites depend on a large number of parameters, both material and morphological, and it is difficult to isolate the consequences of changes in individual variables experimentally. Research was carried out to directly calculate deformation behavior and ductility in terms of parameters characterizing measurable features of the composite's microstructure. Three classes of studies were performed: (i) continuum modeling of deformation and fracture in metal-matrix composites, including the interaction between failure mechanisms using phenomenological constitutive relations to characterize each of the main failure modes in metal-matrix composites, reinforcement cracking, interfacial debonding and matrix void nucleation, growth and coalescence; (ii) numerical studies of the propagation of fast cracks along and across interfaces, with a particular focus on understanding crack propagation from a brittle phase into a ductile phase; and (iii) discrete dislocation modeling of matrix plastic deformation in metal-matrix composites with micron size reinforcements.

2. Research Description

2.1 Continuum Modeling of Metal-Matrix Composites

In Ref. 1 a three dimensional unit cell model was used to analyze the effect of reinforcement orientation on the tensile response of particle and whisker reinforced metal-matrix composites. The metal-matrix was characterized as an isotropically hardening elastic-viscoplastic solid and the ceramic reinforcement is taken to be isotropic elastic. Perfect bonding between the matrix and the reinforcement was assumed. The numerical results show a strong decrease in tensile stress level for small deviations of the whiskers from perfect alignment with the tensile axis. The tensile stress-strain response becomes rather insensitive to the precise value of the misalignment angle when the misalignment is sufficiently large. These trends were also seen in experiments carried out on SiC whisker reinforced aluminum alloys subject to tension at various angles to the whisker axis.

In previous work, we developed physically based models for each of the main failure mechanisms in metal-matrix composites; (i) the fracture of the reinforcing ceramic, (ii) ductile failure by the nucleation, growth and coalescence of voids within the metallic matrix, and (iii) debonding of the interface between the matrix and the reinforcement. In Ref. [5] the interaction between these mechanisms was considered, within the context of a plane strain unit cell model. Attention was restricted to monotonic loading.

A cohesive surface characterization of the particle-matrix interface was used to allow for interfacial debonding. Additionally, particle cracking was modeled by including an initial crack,

perpendicular to the tensile axis and with a cohesive surface in its initial plane to permit crack growth. Results were presented for a plane strain unit cell model of a metal-matrix reinforced with a 20% area fraction of reinforcing particles.

2.2 Fracture

In order to understand the fracture process in solids consisting of heterogeneous distributions of brittle and ductile phases such as metal-matrix composites, a series of studies was carried out analyzing the propagation of cracks along and across interfaces. In these studies, the focus was on fast fracture as would occur under impact loading conditions. However, it is of interest to note that under quasi-static loading conditions, stable equilibrium solutions may not exist for some cases of interest meaning that crack growth will take place dynamically even under slow loading conditions.

In Ref. 2 dynamic crack growth was analyzed numerically for a plane strain bimaterial block with an initial central crack. The material on each side of the bond line was characterized by an isotropic hyperelastic constitutive relation. A cohesive surface constitutive relation was also specified that relates the tractions and displacement jumps across the bond line and that allows for the creation of new free surface. The resistance to crack initiation and the crack speed history were predicted without invoking any *ad hoc* failure criterion. Full finite strain transient analyses were carried out, with two types of loading considered; tensile loading on one side of the specimen and crack face loading. The crack speed history and the evolution of the crack tip stress state were investigated for parameters characterizing a PMMA/Al bimaterial. Additionally, the separate effects of elastic modulus mismatch and elastic wave speed mismatch on interface crack growth were explored for various PMMA-artificial material combinations. The mode mixity of the near tip fields was found to increase with increasing crack speed and in some cases large scale contact occurred in the vicinity of the crack tip. Crack speeds that exceed the smaller of the two Rayleigh wave speeds were also found. These findings were in remarkable accord with experimental observations.

In Ref. 3 the same problem was considered but with potential surfaces of decohesion are interspersed in the material on either side of the bond line and along the bond line. Three calculations were carried out for a PMMA/Al bimaterial. The imposed loading and the properties of the adjacent materials are kept fixed, while the bond line strength was taken to be ¼, ½ and ¾ of the strength of PMMA. The nominal crack speed decreased with increasing bond line strength. When the bond line strength is ¼ that of PMMA, the crack remains on the bond line although there is an attempt at branching off the bond line. For the intermediate case, a bond line strength ½ that of PMMA, repeated branching of the main crack off the bond line into the PMMA occurred, together with micro-crack nucleation on the bond line. The crack branched off the bond line into the PMMA when its strength was ¾ that of PMMA, with the main direction of growth being parallel to the bond line, but with the crack progressively drifting further into the PMMA.

The effects of material plasticity were considered in Refs. 6 and 7. Two characterizations of strain rate hardening were used; power law strain rate hardening and a combined power law-exponential relation that gives rise to enhanced strain rate hardening at high strain rates. The effects of the strain rate hardening characterization on crack initiation, crack growth and crack arrest were investigated. Enhanced strain rate hardening was found to lead to higher crack speeds, to lower toughness values and to crack tip fields that are more like those for an elastic solid than

for the power law rate hardening solid. Additionally, some parameter studies varying the cohesive surface strength and the material flow strength were carried out. The effective stress intensity factor was found to increase dramatically at a certain value of the crack speed that depends on the cohesive surface strength, the material flow strength, the characterization of strain rate hardening and the impact velocity, but there is a range where the crack speed at which the increase in effective stress intensity factor occurs is not very sensitive to impact velocity. The comparison between the materials with power law strain rate hardening and enhanced strain rate hardening can be regarded as illustrating circumstances where strain rates are below and above the transition strain rate for enhanced strain rate hardening, respectively. In one circumstance, crack arrest occurred for the power law strain rate hardening material but not for the material with enhanced strain rate hardening. Thus, whether or not crack growth rates are fast enough for the near-tip material to enter the enhanced strain rate hardening regime may be a significant factor in determining if crack arrest occurs in a ductile metal.

In Ref. 8 calculations were carried out using various degrees of mesh refinement. The results illustrated that convergence does occur, but also for plastic or viscoplastic solids care is needed to design the mesh to resolve the plastic flow field, which is not necessarily confined to the vicinity of the crack tip.

In Ref. 10 the growth of a crack first in an elastic solid, then across an interface and into an elastic-viscoplastic solid is analyzed numerically. Results were presented for two values of interface strength and for two characterizations of strain rate hardening for the viscoplastic solid; power law strain rate hardening and a combined power law-exponential relation that gives rise to enhanced strain rate hardening at high strain rates. For the higher strength interface the crack grew straight through the interface into the elastic-viscoplastic solid, while for the lower strength interface the crack deflected into the interface. In the circumstances analyzed in Ref. 10, a quasi-static, elastic analysis in the literature gives an accurate prediction of whether the crack will penetrate the interface or deflect into it. It was also found that for a low flow strength material with power law strain hardening, and with the interface strength 25% of the material cohesive strength, the crack arrests at the interface, but eventually propagates through. This suggests the possibility that with an even lower flow strength, the crack might be permanently arrested at the interface. Thus, there may be circumstances where the crack speed in the elastic material plays a determining role in whether or not the crack penetrates the interface - a fast crack would slow down at the interface but penetrate it, while a slower crack would be arrested. For such a composite the impact toughness would be much lower than the quasi-static toughness.

2.3 Discrete Dislocation Modeling of Metal-Matrix Composites

In Refs. 4 and 9 a two-dimensional model composite with elastic reinforcements in a crystalline matrix subject to macroscopic shear was analyzed using both discrete dislocation plasticity and conventional continuum slip crystal plasticity. In the discrete dislocation formulation, the dislocations are modeled as line defects in a linear elastic medium. At each stage of loading, superposition is used to represent the solution in terms of the infinite medium solution for the discrete dislocations and a complimentary solution that enforces the boundary conditions, which is non-singular and obtained from a linear elastic, finite element solution. The lattice resistance to dislocation motion, dislocation nucleation and dislocation annihilation are incorporated into the formulation through a set of constitutive rules. Obstacles leading to possible dislocation pile-ups

are also accounted for. Results were presented for materials with a single slip system. A reinforcement size effect is exhibited by the discrete dislocation based analysis whereas the continuum slip results are size independent. The discrete dislocation results have higher average reinforcement stress levels than do the corresponding continuum slip calculations. Averaging of stress fields over windows of increasing size was used to gain insight into the transition from discrete dislocation controlled to continuum behavior.

In the discrete dislocation formulation the plastic stress-strain response and the evolution of the dislocation structure are outcomes of the boundary value problem solution. By way of contrast, in a continuum formulation the plastic stress-strain response is an input, whereas dislocation analyses typically postulate a dislocation structure

The role played by the material length scale, which enters the discrete dislocation formulation through the Burgers vector, was found to depend on the reinforcement morphology. When the reinforcement blocks all matrix slip planes, the composite has high strain hardening and there is a significant size effect. On the other hand, when a vein of unreinforced matrix material is present, there is a yield point followed by a decrease in flow stress until a steady state is reached, and there is no size effect. Regardless of the reinforcement morphology, the composite hardening is size independent in classical continuum plasticity. The results also suggest that continuum analyses of composite materials with micron size reinforcement may underestimate the stress carried by the reinforcing phase. When the reinforcement blocks all slip planes, there is a high local stress concentration due to the dislocation pile-ups at the particle-matrix interface. These local stress concentrations, which are of significance for reinforcement fracture, are not represented in continuum crystal plasticity solutions. Our analyses provide a basis for understanding the limits of conventional continuum formulations and for assigning the length scale associated with non-standard continuum theories.

3. Publications

1. N. Sørensen, S. Suresh A. Needleman and V. Tvergaard, "Effects of Reinforcement Orientation on the Tensile Response of Metal Matrix Composites," *Materials Science and Engineering*, **A197**, 1-10 (1995).

2. X.-P. Xu and A. Needleman, "Numerical Simulations of Dynamic Crack Growth Along an Interface," *International Journal of Fracture*, **74**, 289-324 (1996).

3. X.-P. Xu and A. Needleman, "Numerical Simulations of Dynamic Interfacial Crack Growth Allowing for Crack Growth Away from the Bond Line," *International Journal of Fracture*, **74**, 253-275 (1995).

4. E. van der Giessen and A. Needleman, "Discrete Dislocation Plasticity: A Simple Planar Model," *Modelling and Simulation in Materials Science and Engineering*, **3**, 689-735 (1995).

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6. T. Siegmund and A. Needleman, "Numerical Studies of Fast Crack Growth in Elastic-Plastic Solids," in *Proceedings IUTAM Symposium on Nonlinear Analysis of Fracture*, (ed. by. J.R. Willis), Kluwer, The Netherlands, 211-220 (1997).

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8. A. Needleman, "Cohesive Surface Modeling of Fast Crack Growth," *Computational Mechanics*, **19**, 463-469 (1997).

9. H.H.M. Cleveringa, E. van der Giessen and A. Needleman, "Comparison of Discrete Dislocation and Continuum Plasticity Predictions for a Composite Material," *Acta Materialia*, **45**, 3163-3179 (1997).

10. T. Siegmund, N.A. Fleck and A. Needleman, "Dynamic Crack Growth Across an Interface," *International Journal of Fracture*, to be published.